Shift Scheduling in Pediatric Emergency Medicine

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- Hannah Schapiro
- Aaron Cohen
Content

• Background
• Motivation
• Formulations
  – Weighted Sum method
  – Metric constraints method
• Result
• Future Research
  – Pareto method
Resident Responsibilities in the U-M Pediatric Emergency Department

• 3-7 year medical training program
  – Responsibilities differ by residency year
• Balancing patient care and educational requirements
  – In hospital
    • Caring for patients
    • Teaching medical students
    • Learning from attending physicians
  – Out of hospital
    • Community clinics
    • Conferences
    • Other educational requirements
Pediatric ED: Scheduling Considerations

• All shifts assigned to a resident
• Appropriate coverage
  – e.g. certain shifts require a senior resident
• ACGME rules (similar to ABET for engineering)
  – e.g. 10 hour break rule
• Several different residency programs
  – Pediatrics (PED)
  – Family practice (FP)
  – Emergency medicine (EM)
• And others
Motivation

• Scheduling residents
  – Complicated requirements (UM Pediatric ED)
    • 25 governing rules and preferences
      – Educational goals
      – Patient care
      – Regularization / Safety
  – Chief resident built monthly schedule by hand
    • Time consuming process: 20 - 25 hours / month
    • Transfer every year: no scheduling experience in July
    • Guess and check: errors / tedious correction process

Mixed Integer Programming
Motivation

• Practical Significance
  – Poor-quality schedule
    • Residents: decreased interest in learning
    • Patients: adverse health events
      (Smith-Coggins R, et. al. (1994) : "Relationship of day versus night sleep to physician performance and mood." Annals of Emergency Medicine)

• Goals
  – Solves for feasible schedule quickly
  – Create a good quality schedule with no violations
Formulation: Problem Size

- **Sets**
  - R: set of residents
    - 15-25 residents
  - D: set of days in the schedule
    - 35 days
  - S: set of shifts
    - 8 shifts

- **Decision Variables**
  - Binary: \( x_{rds} \in \{0, 1\} \)
    - 1 if resident \( r \) works shift \( s \) on day \( d \)
    - 0 otherwise

<table>
<thead>
<tr>
<th>Residents Name</th>
<th>Smith</th>
<th>Sanchez</th>
<th>Chen</th>
<th>Shah</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smith</td>
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<tr>
<td>Sanchez</td>
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</tbody>
</table>

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<thead>
<tr>
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<th>27th</th>
<th>...</th>
<th>1st</th>
<th>...</th>
<th>31st</th>
</tr>
</thead>
<tbody>
<tr>
<td>7a-4p</td>
<td>Shah</td>
<td>...</td>
<td></td>
<td></td>
<td>...</td>
</tr>
<tr>
<td>9a-6p</td>
<td>Joe</td>
<td>...</td>
<td></td>
<td>...</td>
<td>Shah</td>
</tr>
<tr>
<td>10a-7p</td>
<td></td>
<td>...</td>
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<td>...</td>
<td></td>
</tr>
<tr>
<td>12p-9p</td>
<td>Chen</td>
<td>...</td>
<td>...</td>
<td>Chen</td>
<td></td>
</tr>
<tr>
<td>4p-1a</td>
<td>Smith</td>
<td>...</td>
<td>Sanchez</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>5p-2a</td>
<td></td>
<td>...</td>
<td></td>
<td>...</td>
<td>Sanchez</td>
</tr>
<tr>
<td>8p-5a</td>
<td>Sanchez</td>
<td>...</td>
<td>Smith</td>
<td>...</td>
<td>Smith</td>
</tr>
<tr>
<td>11p-8a</td>
<td></td>
<td>...</td>
<td>Chen</td>
<td>...</td>
<td>Joe</td>
</tr>
</tbody>
</table>
Objectives: Shift Fairness

- **Total / night shift equity**
  - Equal opportunities for training
  - Improved morale and learning ability

<table>
<thead>
<tr>
<th>Resident Name</th>
<th>Smith</th>
<th>Jones</th>
<th>Chen</th>
<th>Joe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Night Shifts / Total Shifts</td>
<td>0 / 7</td>
<td>1 / 7</td>
<td>1 / 7</td>
<td>5 / 7</td>
</tr>
</tbody>
</table>

- **Total shift equity (TSE):** \( \sum t_{ij}, t_{ij} = |D_i - D_j|, \ i > j \)
- **Night shift equity (NSE):** \( \sum n_{ij}, n_{ij} = |N_i - N_j|, \ i > j \)
Objectives: Undesired Shift

- Bad sleep patterns and post-clinic shifts
  - Improves resident quality of life
  - Increases patient safety

<table>
<thead>
<tr>
<th>Day</th>
<th>Monday</th>
<th>Tuesday</th>
<th>Sleep Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIGHT</td>
<td>1AM – 10AM</td>
<td>Wake-up</td>
<td></td>
</tr>
<tr>
<td>Day</td>
<td>1PM – 10PM</td>
<td>Sleepy</td>
<td></td>
</tr>
</tbody>
</table>

Bad sleep pattern

- Minimum bad sleep patterns (BSP): \(\sum \text{count}\)
Objectives: Undesired Shift

• Bad sleep patterns and post-clinic shifts
  – Improves resident quality of life
  – Increases patient safety

– Minimum post-clinic shifts (PCC): \( \sum \text{count} \)
Formulation: Constraints

• Constraints (rules/requirements)
  – One resident assigned to each shift in the month
    • \( \sum_{r \in \{\text{all}\}} x_{rds} = 1, \forall d, \forall s \)
  – Meets shift requests
    • \( x_{rds} = 0, \forall r, \forall d, s \in \{\text{day off, conferences, continuity clinic}\} \)
  – Ensure resident type appropriate for shift
    • \( \sum_{r \in \{\text{PED}\}} \sum_{s \in P} x_{rds} \geq 1, \forall d, P = \{\{7a,9a\}, \{4p,5p\}, \{8p,11p\}\} \)
  – Intern-forbidden shifts
    • \( \sum_{r \in \{\text{interns}\}} \sum_{d} x_{rds} = 0, \forall s \in \{7a,11p\} \)
  – And others
Multi-Criteria Problem

- Multi-Criteria schedule
  - Metrics for UM Pediatric Emergency Department
    - Total shift equity (TSE)
    - Night shift equity (NSE)
    - Minimum bad sleep patterns (BSP)
    - Minimum post-clinic shifts (PCC)
    - …

Weights? Preferences? Trade-off?

Multi-objective Mathematical Programming
Weighted Sum Method

\[
\text{Min } w_1(TSE) + w_2(NSE) + w_3(BSP) + w_4(PCC) \\
\text{s. t. } \text{"rules/requirements"} \\
x_{rds} \in \{0,1\}
\]

• Quantifying preferences \((w_i)\) is difficult
  – Weights are subjective and difficult to quantify
    • Resulting schedule does not match their intentions
  – Various measurement units
    • Equity \((\sigma, \text{Max} |\text{diff}_{ij}|, \Sigma |\text{diff}_{ij}|, \ldots)\)
Optimized Residency Scheduling Assistant (ORSA): Metrics Formulation

• Feasibility problem
  – Constraint on metrics

\[
\begin{align*}
\text{Min } & w_1(TSE) + w_2(NSE) + w_3(BSP) + w_4(PCC) \\
\text{s.t. } & "\text{rules/requirements}" \\
& x_{rds} \in \{0,1\}
\end{align*}
\]

• Benefits of a feasibility problem
  – More flexible
  – Faster to solve: < 2 sec.
    • Given: 35 days / 20 PEDs / 8 shifts
Optimized Residency Scheduling Assistant (ORSA): Metrics Formulation

• Feasibility problem
  – Constraint on metrics
    
    $\min w_1(TSE) + w_2(NSE) + w_3(BSP) + w_4(PCC)$
    
    s.t.
    
    "rules/requirements"
    
    $x_{rds} \in \{0,1\}$
    
    $lb_{TSE} \leq (TSE) \leq ub_{TSE}$
    
    $lb_{NSE} \leq (NSE) \leq ub_{NSE}$
    
    $lb_{BSP} \leq (BSP) \leq ub_{BSP}$
    
    $lb_{PCC} \leq (PCC) \leq ub_{PCC}$

• Benefits of a feasibility problem
  – More flexible
  – Faster to solve: < 2 sec.
    • Given: 35 days / 20 PEDs / 8 shifts
Optimized Residency Scheduling Assistant (ORSA) : Interactive Improvement

- Example output of metrics
  - Value (Lower bound, Upper bound)

<table>
<thead>
<tr>
<th>Resident Name</th>
<th>Number of Shifts</th>
<th>Number of Night Shifts</th>
<th>Number of Post CC</th>
<th>Number of Bad Sleep Templates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smith</td>
<td>8 (7,9)</td>
<td>2 (0,10)</td>
<td>0 (0,1)</td>
<td>1 (0,1)</td>
</tr>
<tr>
<td>Sanchez</td>
<td>8 (7,10)</td>
<td>1 (0,10)</td>
<td>0 (0,1)</td>
<td>1 (0,1)</td>
</tr>
<tr>
<td>Chen</td>
<td>8 (7,9)</td>
<td>5 (0,10)</td>
<td>1 (0,1)</td>
<td>1 (0,1)</td>
</tr>
<tr>
<td>Shah</td>
<td>14 (13,15)</td>
<td>3 (0,10)</td>
<td>1 (0,1)</td>
<td>1 (0,1)</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

- Interactive approach engaging chief resident
  - Iteratively adjust bounds on metric constraints
  - Quickly build high quality schedule
Optimized Residency Scheduling Assistant (ORSA) : Interactive Improvement

• Interactive Feedback
  – Chief resident identifies undesirable qualitative characteristics

\[
\begin{align*}
\Delta \text{Value} & \uparrow \quad \downarrow \quad \uparrow \quad \ldots \\
\Delta \text{Value} & \downarrow \quad \uparrow \quad \downarrow \quad \ldots \\
\Delta \text{Value} & \downarrow \quad \uparrow \quad \downarrow \quad \ldots
\end{align*}
\]
ORSA Methodology

\[ L_b \leq (Equity) \leq U_b \]
\[ L_b \leq (BSPs) \leq U_b \]
\[ L_b \leq (PostCC) \leq U_b \]

Build a schedule

Adjust or relax constraints

Is it feasible?

Yes → Generate outputs

(Squeezing)

Scheduler

Adjust total shift per resident

Adjust night shift per resident

Adjust BSPs or PCCs metric

Adjust Others

No

Chief Resident

Total Shift Equity?

BSPs or PCCs?

Night Shift Equity?

Others?

Yes → END

Schedule & Metrics report

<table>
<thead>
<tr>
<th>Schedule</th>
<th>TSE</th>
<th>CC</th>
<th>BSPs</th>
<th>…</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sched. A</td>
<td>7</td>
<td>4</td>
<td>2</td>
<td>…</td>
</tr>
<tr>
<td>Sched. B</td>
<td>7</td>
<td>5</td>
<td>1</td>
<td>…</td>
</tr>
<tr>
<td>Sched. C</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>…</td>
</tr>
</tbody>
</table>
ORSA: Results

• Our metrics-based scheduling tool:
  – Reduces time to create schedules
    20 hours/month $\rightarrow$ 1 hour/month
  – Solves a multi-criteria scheduling problem

![Graphs showing reductions in standard deviation and count per resident per day for Total Shift Disparity, Night Shift Disparity, Bad Sleep Patterns, and Post-Clinic Shifts with ORSA compared to without ORSA.](image)
ORSA: Limitations

• **Myopic Solution**
  – Non-Pareto solution could be selected by a chief residents
    • Never see the whole picture (the set of Pareto solutions)
    • The most preferred solution is “most preferred” with respect to their satisfaction
• Pareto Solutions
  – Generate the Pareto solutions of the problem (all of them or a sufficient representation)
  • Select the most preferred one among them

$$f_1(x)$$

$$f_2(x)$$

$$z^I = (z^I_1, z^I_2)$$

$$z^N = (z^N_1, z^N_2)$$

Efficient Schedules
Pareto: Bi-Objective Problem

• Notation
  – \( \mathcal{H} \) : Solution Space, the set of feasible solutions
  – \( \mathcal{P} \) : Pareto Set
  – \( z_i = f_i(x) \) : \( i \)th integer objective function, \( \in \mathbb{Z} \)
  – Dominance (\( \prec \)) : \( x \prec x' \) if and only if \( z_i \leq z_i' \) where at least one inequality is strict

• Bi-Objective Problem
  \[
  \min f(x) = (f_1(x), f_2(x)) \\
  s.t. x \in \mathcal{H}
  \]
Pareto: Bi-Objective Problem

• Pareto Square Region
  – Ideal Point:
    • \( z_1^* = \min_{x \in \mathcal{H}} f_1(x) \) and \( z_2^* = \min_{x \in \mathcal{H}} f_2(x) \)
  – Nadir Point:
    • \( \tilde{z}_1 = \min_{x \in \mathcal{H} \cap f_2(x) = z_2^*} f_1(x) \) and \( \tilde{z}_2 = \min_{x \in \mathcal{H} \cap f_1(x) = z_1^*} f_2(x) \)
Pareto: Bi-Objective Problem

• Pareto Square Region
  – Ideal Point:
    • $z_1^* = \min_{x \in \mathcal{H}} f_1(x)$ and $z_2^* = \min_{x \in \mathcal{H}} f_2(x)$
  – Nadir Point:
    • $\bar{z}_1 = \min_{x \in \mathcal{H} \cap f_2(x) = z_2^*} f_1(x)$ and $\bar{z}_2 = \min_{x \in \mathcal{H} \cap f_1(x) = z_1^*} f_2(x)$
Pareto: Bi-Objective Problem

- Pareto Square Region
  - Ideal Point:
    \[ z_1^* = \min_{x \in \mathcal{H}} f_1(x) \quad \text{and} \quad z_2^* = \min_{x \in \mathcal{H}} f_2(x) \]
  - Nadir Point:
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  - Nadir Point:
    \[ \bar{z}_1 = \min_{x \in \mathcal{H} \cap \{ f_2(x) = z_2^* \}} f_1(x) \text{ and } \bar{z}_2 = \min_{x \in \mathcal{H} \cap \{ f_1(x) = z_1^* \}} f_2(x) \]
Pareto: Bi-Objective Problem

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  - Nadir Point:
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Pareto: Bi-Objective Problem

• **Pareto Squeezing Algorithm**

**Algorithm 1** Exact squeezing algorithm for bi-objective problems

Let $P$ is set of pareto solutions we’ve found;

Compute the ideal $(\hat{z}_1^*, \hat{z}_2^*)$ and Nadir $(\bar{z}_1, \bar{z}_2)$ points;
Set $P := \{(\bar{z}_1, \bar{z}_2)\}$ and $\delta := z_1 - 1$;

WHILE $\delta \geq z_1^*$

   Solve $P_2(\delta)$ and get optimal solution $(\bar{z}_1^*, \bar{z}_2^*)$ to $P_2(\delta)$;

   //Given $(\bar{z}_1^*, \bar{z}_2^*)$, Find a left-bottom corner $(\bar{z}_1^1)$ in the Pareto set;

   Solve $SQZ_1(\bar{z}_2^*)$ and get optimal solution $(\bar{z}_1^1, \bar{z}_2^*)$ to $SQZ_1(\bar{z}_2^*)$;

END WHILE

Set $P := P + (\bar{z}_1^1, \bar{z}_2^*)$ and $\delta = \bar{z}_1^1 - 1$;
GO Step 2 UNTIL $\bar{z}_1 = z_1^*$;
Pareto: Bi-Objective Problem

• Pareto Squeezing Algorithm

**Algorithm 1** Exact squeezing algorithm for bi-objective problems

Let $P$ is set of pareto solutions we’ve found;

- Compute the ideal $(z_1^*, z_2^*)$ and Nadir $(\bar{z}_1, \bar{z}_2)$ points;
- Set $P := \{(\bar{z}_1, z_2^*)\}$ and $\delta := z_1^* - 1$;
- WHILE $\delta \geq z_1^*$
  - Solve $P_2(\delta)$ and get optimal solution $(z_1^*, z_2^*)$ to $P_2(\delta)$;
  - //Given $(z_1^*, z_2^*)$, find a left-bottom corner $(\bar{z}_2^*)$ in the Pareto set;
  - Solve $SQZ_1(z_2^*)$ and get optimal solution $(\bar{z}_1^*, z_2^*)$ to $SQZ_1(z_2^*)$;

END WHILE

- Set $P := P + (\bar{z}_1^*, z_2^*)$ and $\delta := \bar{z}_1^* - 1$;
- GO Step 2 UNTIL $\bar{z}_1 = z_1^*$;

\[
\delta = \bar{z}_1 - 1
\]

\[
\min f_2(x) \quad \text{s.t.} \quad x_1 \leq \delta
\]

\[
\Delta = -1
\]
Pareto: Bi-Objective Problem

- **Pareto Squeezing Algorithm**

  **Algorithm 1** Exact squeezing algorithm for bi-objective problems

  Let $P$ is set of pareto solutions we’ve found;
  
  Compute the ideal $(z_1^*, z_2^*)$ and Nadir $(\bar{z}_1, \bar{z}_2)$ points;
  Set $P := \{(\bar{z}_1, z_2^*)\}$ and $\delta := \bar{z}_1 - 1$;
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  Solve $P_2(\delta)$ and get optimal solution $(z_1^*, z_2^*)$ to $P_2(\delta)$;
  //Given $(z_1^*, z_2^*)$, find a left-bottom corner $(\tilde{z}_1^*)$ in the Pareto set;
  Solve $SQZ_1(z_2^*)$ and get optimal solution $(\tilde{z}_1^*, z_2^*)$ to $SQZ_1(z_2^*)$;
  
  END WHILE
  
  Set $P := P + (\tilde{z}_1^*, z_2^*)$ and $\delta := \tilde{z}_1^* - 1$;
  
  GO Step 2 UNTIL $\bar{z}_1 = z_1^*$;
Pareto: Bi-Objective Problem

- Pareto Squeezing Algorithm

**Algorithm 1** Exact squeezing algorithm for bi-objective problems

Let \( P \) is set of pareto solutions we’ve found;

Compute the ideal \((\hat{z}_1^1, z_2^1)\) and Nadir \((\tilde{z}_1, \tilde{z}_2)\) points;
Set \( P := \{ (\hat{z}_1, z_2^1) \} \) and \( \delta := \hat{z}_1 - 1 \);

**WHILE** \( \delta \geq \hat{z}_1^1 \) 

- Solve \( P_2(\delta) \) and get optimal solution \((z_1^1, z_2^1)\) to \( P_2(\delta) \);
- Given \((z_1^1, z_2^1)\), Find a left-bottom corner \((\hat{z}_1)\) in the Pareto set;
- Solve \( SQZ_1(\hat{z}_1^1) \) and get optimal solution \((\hat{z}_1^1, z_2^1)\) to \( SQZ_1(\hat{z}_1^1) \);

**END WHILE**

Set \( P := P + (\hat{z}_1^1, z_2^1) \) and \( \delta := \hat{z}_1^1 - 1 \);

GO Step 2 UNTIL \( \hat{z}_1 = \hat{z}_1^1 \);
Pareto: Bi-Objective Problem

- **Pareto Squeezing Algorithm**

  **Algorithm 1** Exact squeezing algorithm for bi-objective problems

  Let $P$ is set of pareto solutions we’ve found;

  Compute the ideal $(z_1^*, z_2^*)$ and Nadir $(\bar{z}_1, \bar{z}_2)$ points;
  Set $P := \{ (\bar{z}_1, z_2^*) \}$ and $\delta := \bar{z}_1 - 1$;
  **WHILE** $\delta \geq z_1^*$
  
  Solve $P_2(\delta)$ and get optimal solution $(z_1^\delta, z_2^\delta)$ to $P_2(\delta)$;
  //Given $(z_1^\delta, z_2^\delta)$, Find a left-bottom corner $(\hat{z}_1^\delta)$ in the Pareto set;
  Solve $SQZ_1(z_2^\delta)$ and get optimal solution $(\hat{z}_1^\delta, \hat{z}_2^\delta)$ to $SQZ_1(z_2^\delta)$;

  **END WHILE**
  
  Set $P := P + (\hat{z}_1^\delta, z_2^\delta)$ and $\delta := \hat{z}_1^\delta - 1$;
  **GO** Step 2 **UNTIL** $z_1 = z_1^*$;
Pareto: Bi-Objective Problem

- Pareto Squeezing Algorithm

**Algorithm 1** Exact squeezing algorithm for bi-objective problems

Let $P$ is set of pareto solutions we’ve found;

1. Compute the ideal $(z_1^*, z_2^*)$ and Nadir $(\tilde{z}_1, \tilde{z}_2)$ points;
2. Set $P := \{(z_1, z_2)\}$ and $\delta := \tilde{z}_1 - 1$;
3. WHILE $\delta \geq z_1^*$
   - Solve $P_2(\delta)$ and get optimal solution $(z_1^1, z_2^1)$ to $P_2(\delta)$;
   - Given $(z_1^1, z_2^1)$, Find a left-bottom corner $(\tilde{z}_1^1)$ in the Pareto set;
   - Solve $SQZ_1(\tilde{z}_1^1)$ and get optimal solution $(\tilde{z}_1^1, \tilde{z}_2^1)$ to $SQZ_1(\tilde{z}_1^1)$;
4. END WHILE
5. Set $P := P + (\tilde{z}_1^1, \tilde{z}_2^1)$ and $\delta := \tilde{z}_1^1 - 1$;
6. GO Step 2 UNTIL $\tilde{z}_1 = z_1^*$;
Pareto: Tri-Objective Problem

• "Pareto Cone"

  – Given fixed $z$ level, bi-objective problem

  \[ \begin{align*}
  f_1(x) & = z_1^*, \\
  f_2(x) & = z_2^* \\
  z^* & = (z_1^*, z_2^*) \\
  \bar{z} & = (\bar{z}_1, \bar{z}_2) \\
  \end{align*} \]
Acknowledgements

• Thank you to CHEPS, TDC Foundation, the Bonder Foundation, and Dr. Brian Jordan, Dr. Micah Long, Dr. Jenny Zank and Dr. Ed O'Brien for making this research possible.
CHEPS and the HEPS Master’s Program

- **CHEPS**: The Center for Healthcare Engineering and Patient Safety
- **HEPS**: Industrial and Operations Engineering (IOE) Master’s Concentration in Healthcare Engineering and Patient Safety offered by CHEPS
- CHEPS and HEPS offer unique multidisciplinary teams from engineering, medicine, public health, nursing, and more collaborating with healthcare professionals to better provide and care for patients
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Thank You!
Feedback and Questions

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